and tends to fit high-order acceleration terms almost as well as the 7-point method. The smoothing function is very easy to implement; it consists only of multiplying each of the nine values by a constant, summing the new values, and dividing the sum by a constant. For the improvement one obtains as compared to the cost of implementation in the DTS, the 9-point method appears most desirable and should be the standard method of obtaining counted doppler.

References

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3. Semtner, A. J., *Polynomial Smoothing Formulas and Derivative Formulas for One or Two Independent Variables*, Technical Report 32-1312. Jet Propulsion Laboratory, Pasadena, Calif., Nov. 15, 1968.

4. Telemetry Improvement Proposal for the 85-ft Antenna Network, J. M. Urech

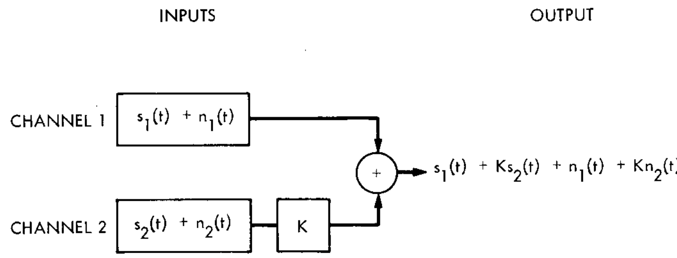
a. Introduction. Since most of the spacecraft currently being tracked at the Madrid stations are either near or below the telemetry threshold, studies and tests have been carried out to ascertain the possibility of combining two or more stations to improve telemetry performance. The studies show that telemetry performance can be improved by several decibels, depending on which of the proposed methods of combination is selected. As discussed in *Paragraph b*, an increase of 3 dB over a normal two-way tracking station can be obtained with the combined tracking of two identical stations—one in normal two-way (acting as prime) and the other in three-way (acting as booster). With the configuration of one station in a *receive only* mode (with diplexer bypass) acting as the "booster station," a 4.75-dB improvement may be obtained.

A 3-dB improvement in telemetry means that:

(1) For equal amounts of information, its quality will be much better when spacecraft signal is very close to or below telemetry threshold. The number of telemetry errors may be reduced by a factor as great as 100 depending on the initial operating point.

(2) For the same quality of information, the quantity of information obtained may be doubled. This is possible because the spacecraft can be switched to double bit rate.

b. Basic theory. The basic theory consists of combining two copies (or versions) of the same spacecraft signal which has been affected by *two independent noise contributions.*



(K = VARIABLE GAIN FOR CHANNEL 2)

We will suppose that both channels are initially adjusted in order to have $s_1(t) = s_2(t) = s(t)$.

Let us see the signal-to-noise ratio (SNR) at the inputs and output:

$$SNR_1 = \frac{\overline{s_1(t)^2}}{\overline{n_1(t)^2}} = \frac{\overline{s(t)^2}}{\overline{n_1(t)^2}}$$

$$SNR_2 = \frac{\overline{s_2(t)^2}}{\overline{n_2(t)^2}} = \frac{\overline{s(t)^2}}{\overline{n_2(t)^2}}$$

In the general case they may be different by a factor of a:

$$SNR_1 = a\, SNR_2 \tag{1}$$

The output signal power is

$$S_{out} = \overline{[s_1(t) + Ks_2(t)]^2} = \overline{s(t)^2}\,(1 + K)^2$$

The output noise power is

$$N_{out} = \overline{[n_1(t) + Kn_2(t)]^2} = \overline{n_1(t)^2} + K^2\overline{n_2(t)^2} + 2K\overline{n_1(t)n_2(t)}$$

but $\overline{n_1(t)n_2(t)} = 0$, as the two noise contributions are assumed to be independent or uncorrelated. Hence, the SNR at the output is

$$SNR_{out} = \frac{\overline{s(t)^2}\,(1 + K)^2}{\overline{n_1(t)^2} + K^2\overline{n_2(t)^2}} = \frac{(1 + K)^2}{\dfrac{1}{SNR_1} + \dfrac{K^2}{SNR_2}} = SNR_1 \frac{(1 + K)^2}{1 + aK^2} \tag{2}$$

Let us find the optimum value of K that makes the SNR_{out} maximum:

$$\frac{d(SNR_{out})}{dK} = 0$$

$$2(1 + aK^2)(1 + K) - 2aK(1 + K)^2 = 0$$

$$aK^2 + (a - 1)K - 1 = 0$$

$$K = \begin{cases} \dfrac{1}{a}, \text{ for } SNR_{out} \text{ maximum} \\ -1, \text{ for } SNR_{out} \text{ minimum} \end{cases} \tag{3}$$

Therefore, *the optimum amplitude mixing ratio K must be the inverse of the channel SNR ratio;* that is,

$$K = \frac{SNR_2}{SNR_1}$$

Then, the output signal-to-noise ratio will be

$$SNR_{out} = SNR_1 \frac{\left(1 + \dfrac{1}{a}\right)^2}{1 + \dfrac{1}{a}} = SNR_1 \left(1 + \frac{1}{a}\right) \tag{4}$$

which is always greater than the best channel SNR.

Figure 15, which is a plot of Eq. (2), shows the influence of the mixing ratio and the SNR difference between the two channels on the combination performance. Obviously, the optimization of the mixing ratio should be attempted in each particular case, but this is not a critical parameter since all curves have a very flat maximum.

In the case of both channels having the same SNR (combination of two identical stations, $a = 1$ in Eq. 1), the mixing ratio K must be equal to 1, which when substituted in Eq. (4) gives

$$SNR_{out} = 2SNR$$

which means a 3-dB improvement.

A case of particular interest (both channels having different SNRs) is when one normal two-way tracking station is combined with a booster station in the *receive only* mode with diplexer bypass:

$$SNR_1 \simeq \frac{1}{2} SNR_2$$

The mixing ratio must be equal to 2, which in Eq. (4) gives

$$SNR_{out} = 3SNR_1$$

which is a 4.75-dB improvement over a normal two-way tracking station.

c. Different combination methods. Depending upon the point selected on the information channel for combining the signals of the two stations, four combination methods may be employed:

(1) *RF combination* (S-band or intermediate RF frequency). Theoretically, this is the best method since it simultaneously improves the tracking capability of the receiver. Practically, however, the RF combination cannot be employed due to actual station configurations and locations which inhibit the sustainment of both signals in phase coherency.

(2) *Subcarrier combination.* The subcarrier obtained from the booster station is sent via microwave link to the prime station, where it is combined in a normal linear mixer with the other subcarrier and the result fed into the demodulator equipment. This method is very practical; it can be directly applied to DSS 61/62, as well as Goldstone, and does not require the installation of additional hardware.

The only limitation for stations joined by microwave link is that the time delay between the two signals must be small compared to the subcarrier period. If the delay is long enough to degrade the signal combination, the fixed part of the delay (due to microwave link) can be compensated by an extra delay device. The variable part (due to the different station locations), however, is more difficult to compensate since it will vary with the spacecraft position.

This method is ideal for stations which are located not too far apart and work with projects using a low-frequency subcarrier as in the case of DSSs 61 and 62 with the *Pioneer* Project.

(3) *Bit-stream combination* (before the "match filter" decision). As in the previous method, the booster station

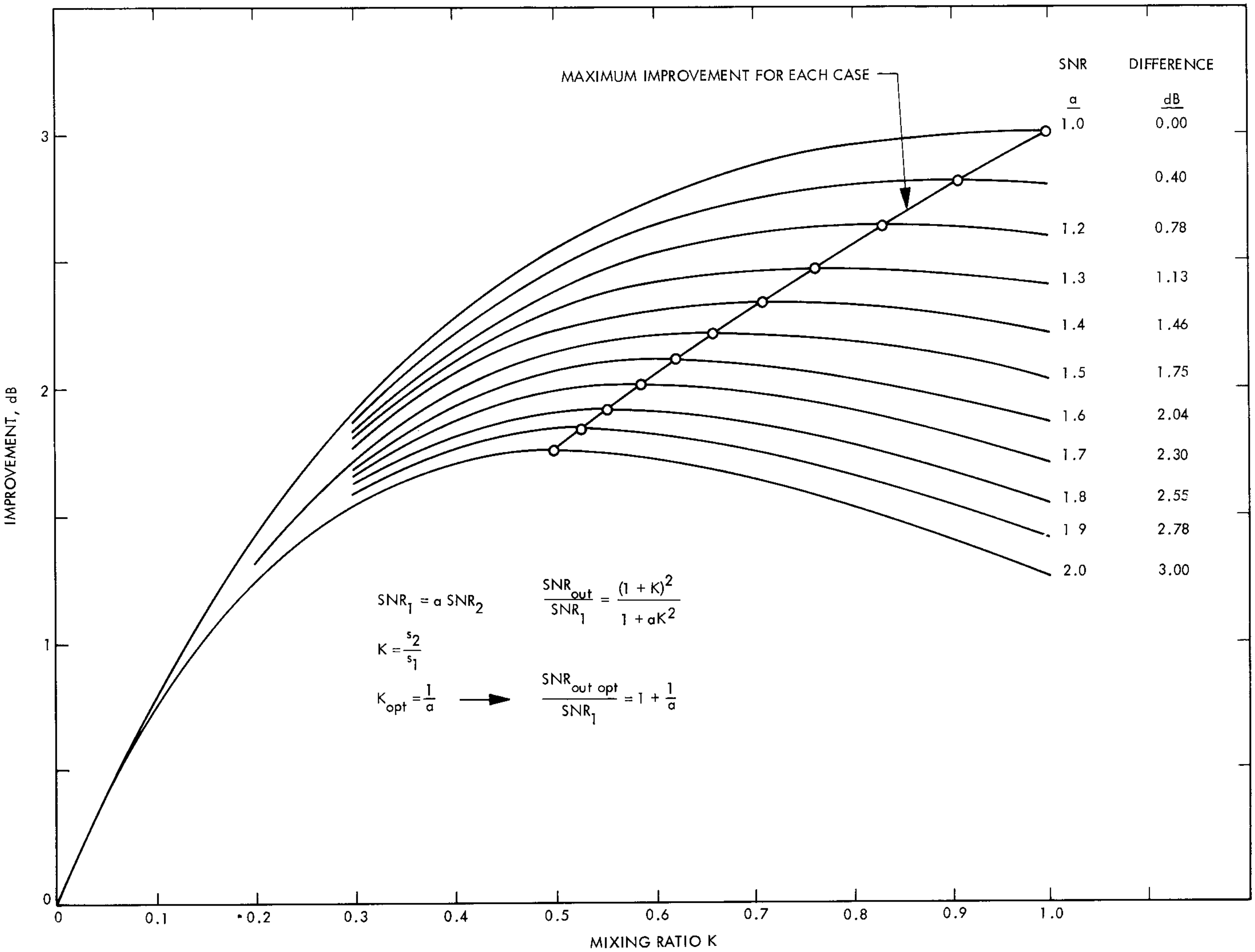


Fig. 15. SNR improvement vs mixing ratio as a function of the SNR difference between the two channels

will send its bit stream via microwave link to the prime station. This method may also be adopted by the Madrid or Goldstone complexes without extra hardware if multiple-mission telemetry (MMT) equipment is used at one or both stations. For the *Pioneer* Project using ground operational equipment (GOE), it will be difficult to implement since complicated internal modifications will be required in the demodulator synchronizer.

Nevertheless, the time delay limitation is not as important as in method 2, because it will normally be much smaller than the bit period.

(4) *Processed data combination.* With this method the two data streams [already processed by the telemetry and command processor (TCP)] are sent via teletype (or high-speed data line) to a central computer located at either of the stations or at the SFOF. The computer will compare both information streams and will select the best data. It is obvious that this method is only applicable to projects using some kind of error detection technique (such as the parity error in *Pioneer*) that will allow the computer to detect an erroneous telemetry word from one channel, omit it, and select the corresponding "good" word from the other. Thus, the probability of having an error after combination will be the probability of having the same word in error in both channels, which, due to independent noise contributions, will be equal to the product of error probabilities for each channel. This telemetry improvement can be shown to be equivalent to the theory presented in *Paragraph b.*

With this method, there is no time delay limitation since the computer may employ a high capacity telemetry buffer.

Stations having a common "view" period (DSS 11/12, DSS 41/42, DSS 51/61/62) may implement this method, with the only drawback being the time required for development of the software.

d. Current status of test phase. The last three methods in *Paragraph c* are in development or test phase. To determine a priority sequence of development for these methods, two prime factors were considered:

(1) Those methods applicable to the *Pioneer* Project—since this is the only type of telemetry we have now available.

(2) Those methods (applicable to *Pioneer*) which can most easily be implemented.

As a result, the following priorities were established:

Priority 1: Method 2, *subcarrier combination.* The telemetry subcarrier from the DSS 62 receiver is sent (as in normal *Pioneer* tracking) via microwave link to the GOE station DSS 61 where it is combined with the DSS 61 subcarrier telemetry in a linear mixer of type EMR model 264A installed in the transfer rack. Input levels to the mixer are adjusted for an optimum mixing ratio and the obtainment of a 1-V p–p output to feed the GOE.

The fixed delay, due to microwave link, is 37 μs; the variable delay, due to the spacecraft location with reference to the stations, may vary from about $+28$ to -28 μs from spacecraft rise to set.

Due to this variable delay, the combination performance from meridian to set will be optimum if DSS 62 is the booster, as this will compensate part of the fixed delay, and also if DSS 61 is the booster from spacecraft rise to meridian.

Several internal telemetry and configuration tests were performed with satisfactory results. As a final test, *Pioneer VIII* was tracked for 2 h on day 54, pass 804, by both stations (in three-way with DSS 51) while the spacecraft was close to the set position. The test was successful as telemetry showed an improvement of 2.7 dB, which is close to the 3-dB gain predicted by theory. On day 67, pass 817, *Pioneer VIII* was tracked for 3 h just prior to the meridian crossing. Results showed a telemetry improvement of about 2.2 dB. These differences are mainly due to the variable delay discussed previously. In order to reduce this effect to a minimum, DSS 61 should act as booster from spacecraft rise to meridian and DSS 62 from meridian to set.

Another test was performed in order to check the practical limitations of this combination method. *Pioneer VI* was tracked on days 66 and 67 for a total of 4 h. Due to the very low signal level (-170 dBmW), the demodulator synchronizer was unable to get in lock with only one station tracking. With the combination of both stations, the subcarrier signal was high enough to bring the demodulator in lock. However, it was not sufficient to obtain valid telemetry from the TCP, since the degradation caused by both receivers working under such marginal conditions (-170 dBmW and system noise temperature of 44°K) was masking most of the station-combination improvement.

To fully ascertain the limits of this method, the test is expected to be reconducted in the near future when a stronger (1 or 2 more dB) spacecraft signal is available.

Priority 2: Method 3, *bit-stream combination,* which may be applied to *Mariner*-type spacecraft, or *Pioneer* using the MMT configuration, has also been implemented as follows: First, the telemetry subcarrier from the DSS 61 receiver is sent via microwave link to DSS 62, where it goes through the up-converter on the MMT test rack to feed subcarrier demodulator assembly (SDA) 2. The input to SDA 1 is the normal input from receiver 1 at DSS 62. Then, the integrated outputs of both SDAs are combined in the transfer rack (through a simple wiring change) to feed the TCP using the MMT Program. (Because of the two possible locking points, 180 deg apart on the SDA, care should be taken after acquisition so that both SDA outputs will have the correct polarity.)

This configuration has been checked with *Pioneer VIII* in one-way on day 67 for 2.5 h, obtaining a telemetry improvement of 2.6 dB, which could still be increased by optimizing the mixing ratio.

This method was checked simultaneously with method 2 on *Pioneer VI*. The combination improvement was on the order of 1.5 dB, giving an average of 4 words in error per telemetry frame.

With more efficient optimization, this method will, in the very near future, be able to obtain usable telemetry.

Priority 3: Method 4, *processed data combination,* will be ideally applicable to two identical stations (two GOE stations or two MMT stations) using a central computer at the SFOF. Nevertheless, for testing purposes, it is being developed at DSS 62.